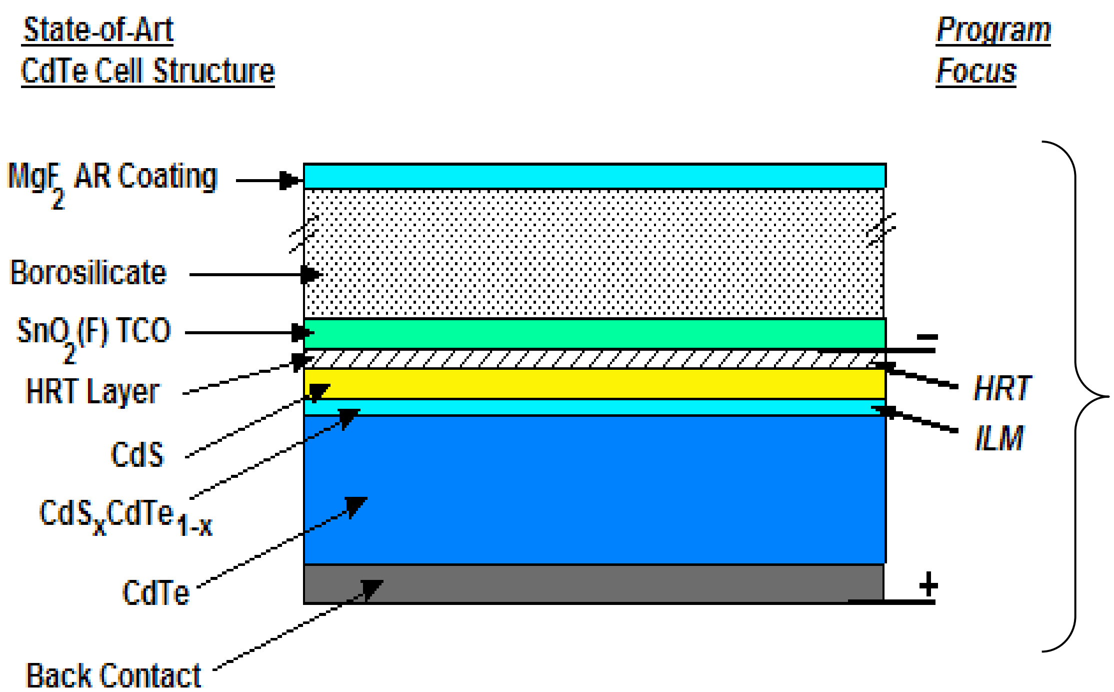

Multilayer Window for Improved Performance in CdTe Solar Cells

Program Team (PV, CSP, Systems Integration, Market Transformation)

John P Lemmon

Pacific Northwest National laboratory

Contact Info

Date

Timeline

- Project start date: 01-20-2010
- Project end date: 09-01-2012
- Percent complete: 12%

Budget

- Total project funding: $750K
  - DOE share: $750K
  - Contractor share: $0
- Funding received in FY09: $0
- Funding for FY10: $250K

Barriers

- Decrease manufacturing cost to <$0.60.
- Increased module efficiency from 11% to 13.5%.
- Limit enabling capital investment.

Partners

- Project lead - PNNL
- Interactions – Institute for Energy Conversion, UD.
  - IEC provides baseline cells, characterization.

Challenges, Barriers or Problems

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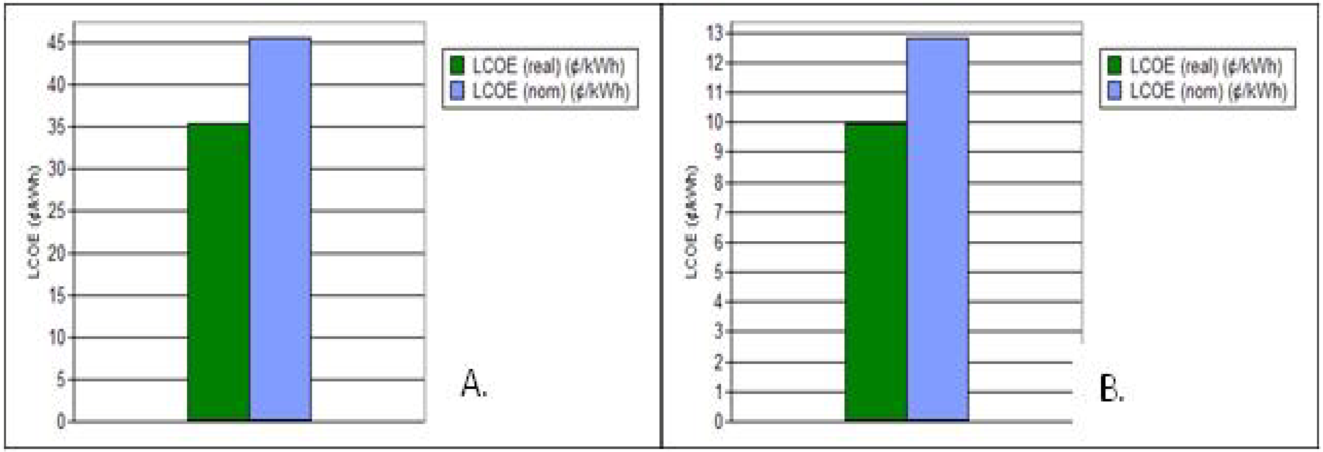
- $0.54/W CdTe manufacturing cost to meet $0.10/kWh LCOE
  - Increased module efficiency from 11% to 13.5% for CdTe.
  - 16% cell efficiency required
- Impact on 2015-2030 PV Goals
  - Improvements in module efficiencies result in LCOE of $0.12/W for commercial market



Graph of the levelized cost of electricity using the NREL SAM program to estimate the impact of a cost reduction to $0.48/Wdc using First Solar FS-55 module. The estimated levelized cost for both A) residential and B) commercial flat plate systems are shown.

Relevance

Overall Program Objective:

Decrease the manufacturing cost of thin film CdTe modules by improving performance and durability, significantly impacting the LCOE (<$0.11/W) meeting 2015 and 2030 PV goals.

Technical Objectives:

- Develop a new multi-layer window that: minimizes recombination at the heterojunction, limits diffusion and phase formation, decreases window absorbance and decreases module performance variability.

- Limit the impact on capital cost of implementing new window technology in current CdTe manufacturing.

Table of top three measured and calculated CdTe solar cells.

Reference	V_{oc} (mV)	J_{sc} (mA/cm^2)	FF (%)	Efficiency (%)	Area (cm^2)
Wu, et. al. (2004)[11]	845.0	25.88	75.51	16.5	1.032
Ohyama, et. al. (1997)[12]	840.3	26.00	73.10	16.0	1.0
Ferekides (1993)[3]	842.9	25.09	74.48	15.8	1.05
McCandless & Sites Theoretical	900	26	80	19	1.0

Single Diode Model of record cells.

Single diode equation:

$$J = J_o \exp[(V-JR)/AkT] - J_{sc} + V/r$$

For Wu Cell

$J_o = 1 \times 10^{-9}$ A/cm^2

A = 1.9

Predicted Cell Losses

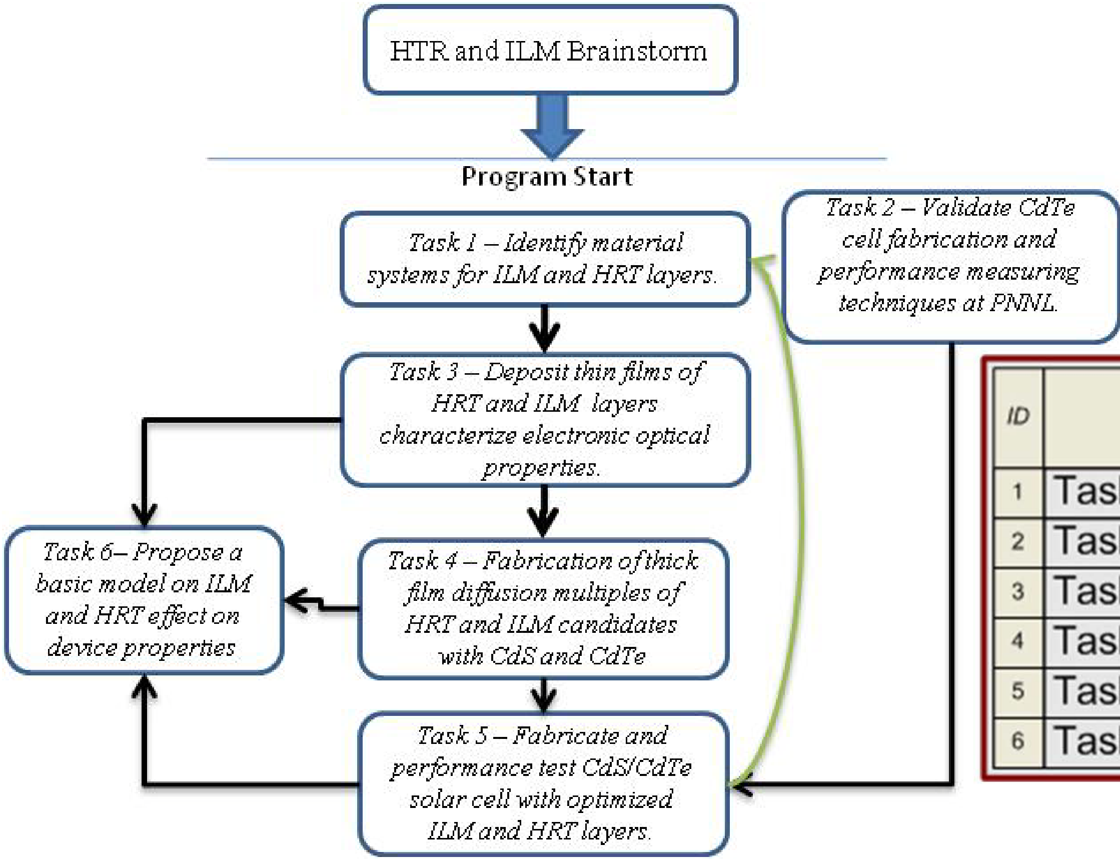
- Quality factor (A) > 1 indicate losses from SRH recombination.
- Recombination via interband states in CdS-CdTe interface.
- Consumption of CdS to form pseudo ternary Cd-Te-S phases, requires thick CdS film.

Efficiency gains can be realized by improving Voc and FF.

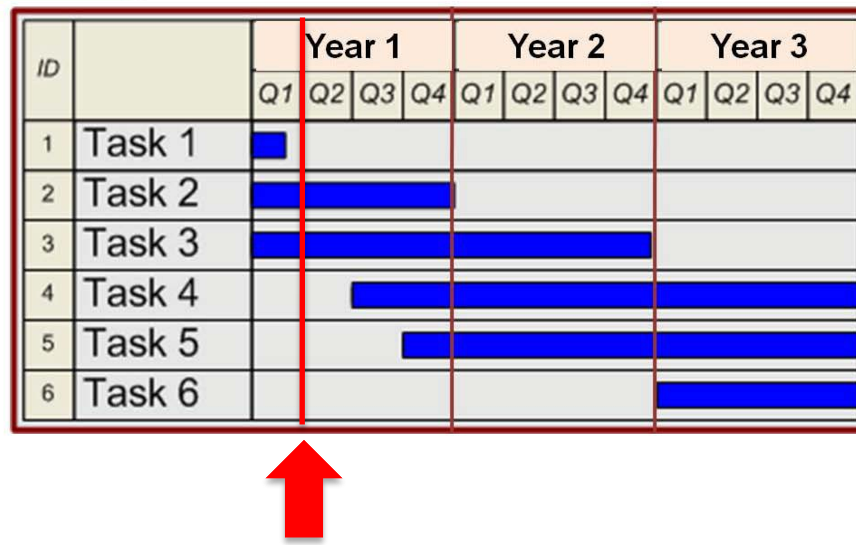
Approach

Task structure and deliverable timing.

Develop Inter Layer Material (ILM) between CdS and CdTe interface to minimize CdS-CdTe diffusion, improving performance and durability.



Accelerated FY10 focused on Tasks 1-4



Project flow and tasks designed to minimize variability while maximizing materials screening for best ILM and HRT candidate systems/

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Approach

Task 1 – Identify material systems for ILM and HRT layers

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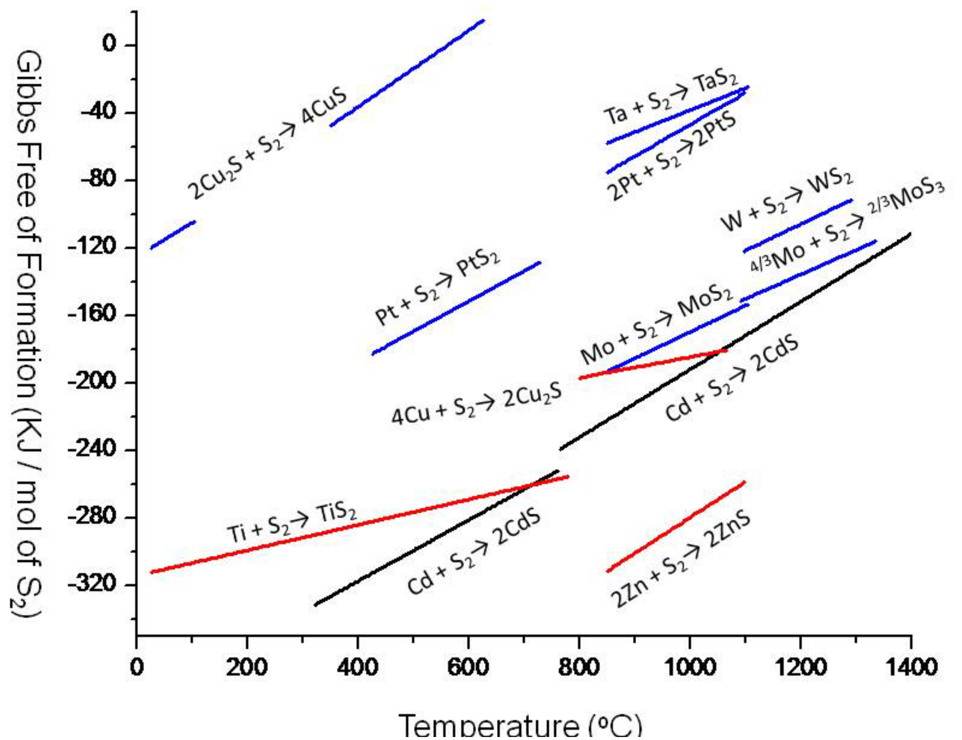
Task	*Rationale*	Approach	*Deliverable*
Task 1	Maximize resources by selecting thermodynamic stable ILM	Identify materials based on literature resources and phase diagram analysis	Materials systems for HRT and ILM layers identified and ranked (Completed 04-20-2010)



Material	Oxides	$\Delta^o{}_fG$ (298 K) [KJ/g-atom]
Native	TeO_2	-90.65
Native	CdO	-112.90
Native	$CdTeO_3$	-112.10
W	WO_2	-178
	WO_3	-191
Mo	MoO_2	-178
	MoO_3	-167
Ta	Ta_2O_5	-273

ILM and HRT candidates based on thermodynamic stability with S and Cd.

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Approach

Task 2. CdTe Baseline Cell Fabrication and Performance.

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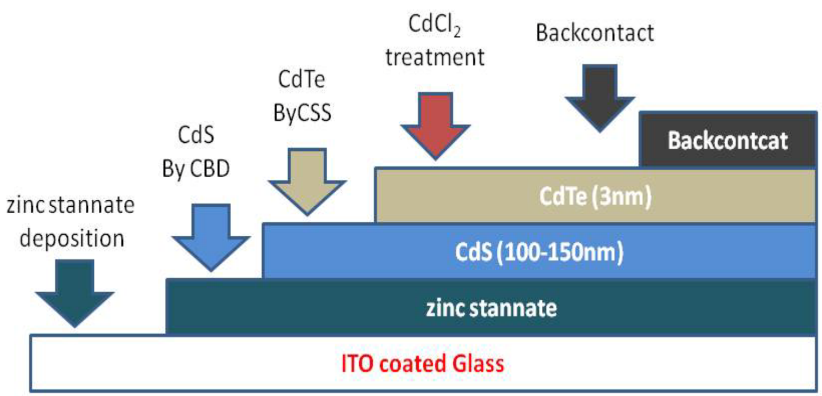
Task	*Rationale*	Approach	*Deliverable*
Task 2	Establish baseline cell fabrication and measurement systems to evaluate ILM impact on performance.	Develop standard operating procedures to ensure consistent film and cell properties	Reproducible PNNL fabricated CdTe cell with an efficiency between 13% - 14% (Due 10-2010)

IEC-PNNL CdTe Fabrication Matrix

Order	ITO	TO	CdS	CdTe	CdCl2	BC	IV	QE	IEC Est $
5	PNNL	IEC	IEC	IEC	IEC	IEC	IEC	IEC	$
4	PNNL	PNNL	IEC	IEC	IEC	IEC	IEC	IEC	$
	PNNL	PNNL	PNNL	IEC	IEC	IEC	IEC	IEC	$
2	PNNL	PNNL	PNNL	PNNL	IEC	IEC	IEC	IEC	$
3	PNNL	PNNL	PNNL	PNNL	PNNL	IEC	IEC	IEC	$
6	PNNL	PNNL	PNNL	PNNL	PNNL	PNNL	IEC-PNNL	IEC-PNNL	$
1	IEC	IEC	IEC	IEC	IEC	IEC	IEC-PNNL	IEC-PNNL	$
5	IEC	PNNL	PNNL	PNNL	PNNL	PNNL	IEC	IEC	$
4	IEC	IEC	PNNL	PNNL	PNNL	PNNL	IEC	IEC	$
	IEC	IEC	IEC	PNNL	PNNL	PNNL	IEC	IEC	$
2	IEC	IEC	IEC	IEC	PNNL	PNNL	IEC	IEC	$
3	IEC	IEC	IEC	IEC	IEC	PNNL	IEC	IEC	$



Establish and validate baseline cell fabrication and measurements with ICE.

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Approach

Task 3. Deposit and characterize ILM and HRT film properties.

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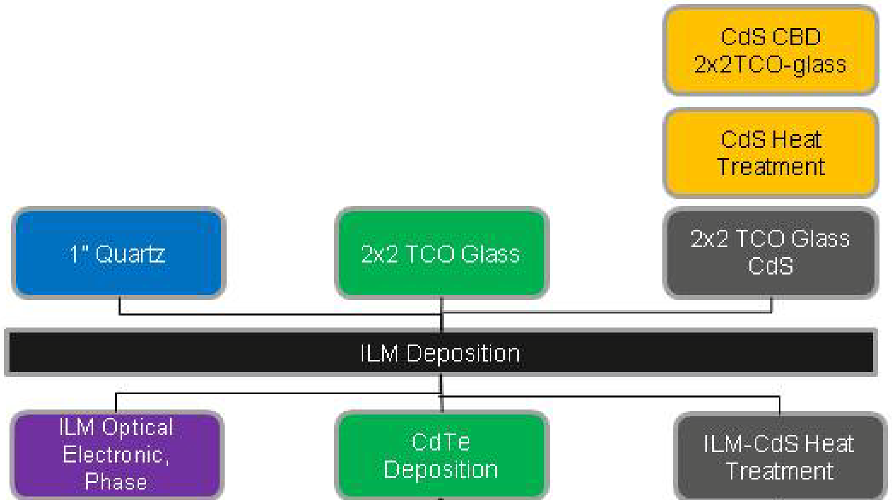
Task	*Rationale*	Approach	*Deliverable*
Task 3	Assess candidate materials properties before being deposited as HRT or ILM in full CdTe cells.	Thin films of candidate systems will be deposited on transparent substrates using a multi-target sputter machine.	Ten candidate material systems that have been optimized for optical and electronic properties for use as HRT or ILM layers. (Due 10-1-2010)



ILM and HRT Film Deposition

- Sputter < 100nm thick films for characterization
- Sputter >1000nm for thick film phase analysis.

Property Measurements for ILM and HRT Film

- Four point probe conductivity
- Optical transmission

Maximize ILM optical transmission while exploring electronic effects.

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Approach

Task 4. Fabricate diffusion multiples of ILM/CdS and ILM/CdTe

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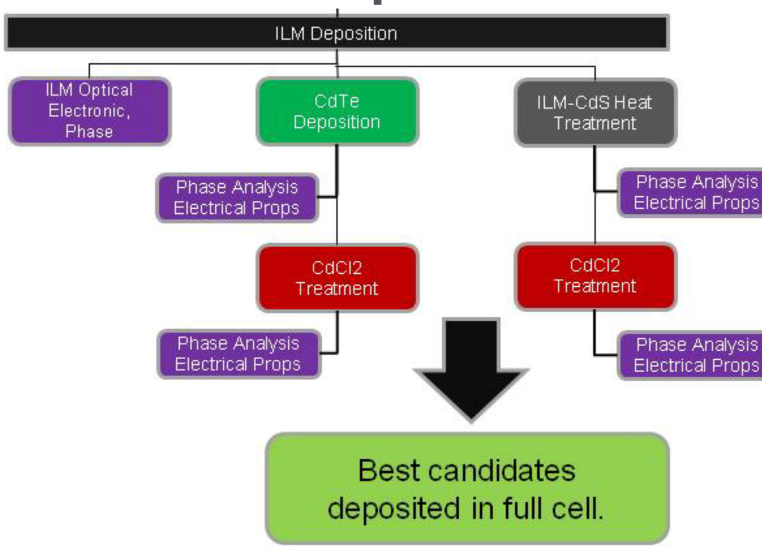
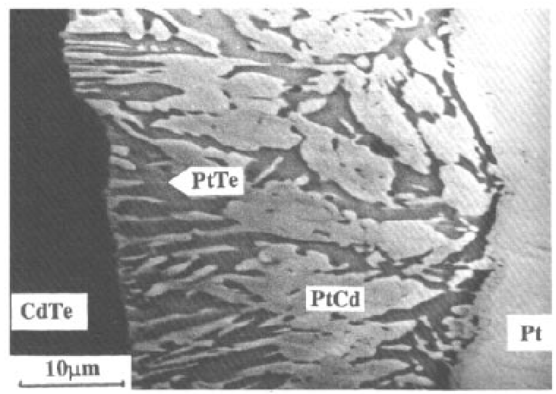
Task	*Rationale*	Approach	*Deliverable*
Task 4	The phase formation with CdS and CdTe for proposed candidates are not known.	ILM diffusion multiple s formed at variable temperatures cross-sectioned diffusion products will be analyzed by SEM and electron microprobe.	Fabricate and analyze 5 candidate HRT and ILM materials for phase formation and reactivity with CdS and CdTe. (Due 10-1-2010)

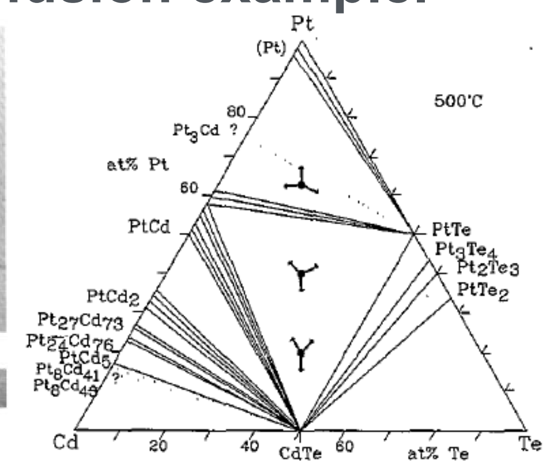
ILM Sample Flow



Pt –CdTe Inter diffusion example.



Cross section SEM Pt-CdTe diffusion at 500C.



Semicond. Sci. Technol. 9 (1994) 2085–2096.

Determine ILM materials that form stable ties lines with CdS and CdTe.

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Collaborations

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Collaboration:

Informal collaboration with Brian McCandless at the Institute for Energy Conversion, University of Delaware.

Purpose of Collaboration:

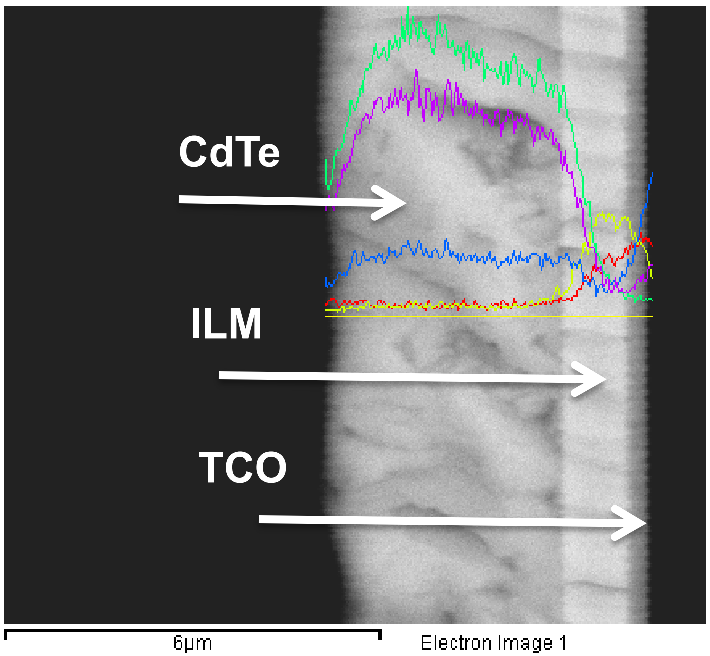
- IEC to provide CdTe cells for round robin of PV performance measurement system.
- PNNL to purchase IEC CdTe based cells in various stages of fabrication to validate fabrication process.
- Develop future collaborative efforts in PV.

Accomplishments / Progress / Results

- Down-selected 20 ILM systems in Task 1.
- Develop procedures for CBD of CdS and CSS of CdTe in Task 2.
- Completed the deposition, optical transmission and electrical measurements of 4 ILM materials in Task 3.
- Completed the fabrication and analysis of 1 ILM material on CdS and CdTe heat treated at 2 different temperatures and 3 different oxygen partial pressures, w/wo $CdCl_2$ treatment in Task 4.
- Begun fabrication of full CdTe PV cell in Task 5.

Thick film ILM and CdTe

- CdTe deposited on ILM - TCO coated glass at 600C, followed by $CdCl_2$ vaporization treatment.



First ILM candidate shows minimal diffusion with CdTe and CdS (not shown). ILM materials is highly transmissive and can possess various electronic state.

Budget Status and Potential for Expansion

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- Total funding of $750K over 2.5yrs from DOE-EERE ARRA
  - New start (January 20, 2010)
  - $0 Cost Share
- FY 2010 budget $250K/yr, currently 27% spent.
- Proposed Expanded Funding activities.
  - Task 4: Provide fundamental interactions and phase formation of CdTe and CdS with ILM layers.
  - Task 5: Provide more ILM incorporated CdTe cell fabrication and testing, increase fundamental mechanisms for improved performance .

FY10 Budget Snapshot

		Funding Authorized	Feb10 Cost	Mar10 Cost	Apr10 cost	FY Total Costs	% Spent by Phase
Year 1	1/20-9/30/10						
	Validation&Performance	$ 50,000	$ -			$ -	0.0%
	Project Management	$ 20,000	$ 1,582	$ 6,882	$ 4,416	$ 12,848	64.2%
	CdTe Deposition	$ 80,000	$ 2,400	$ 10,875	$ 5,579	$ 19,902	24.9%
	ILM Deposition	$ 80,000	$ 1,355	$ 7,755	$ 23,393	$ 31,535	39.4%
	Materials/Waste	$ 20,000	$ 177	$ 1,433	$ 2,213	$ 3,823	19.1%

Future Plans (FY 2011 and beyond)

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- Continuation of Tasks 2-4.
  - Task 2: Fabricate and measure baseline PNNL CdTe cell.
  - Task 3: Complete ILM depositions and characterization of materials selected in Task 1.
  - Task 4: Complete ILM thick film depositions on CdTe and CdS, analyze interface for diffusion.
- Start Task 5.
  - Performance testing of ILM materials in CdTe cells.
- Key Milestones:
  - Establish baseline CdTe cell.
- Remaining issues:
  - Task 2 delayed due to purchase contract negotiations.

Mandatory Summary Slide

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- Program focused on improving Voc and FF by modify window-absorber interface by developing new ILM.
- ILM candidates selected on phase diagram analysis and simple thermodynamics for Task 1.
- Baseline cell fabrication in process for Task 2.
- Optical and electronic properties of four ILM candidates measured for Task 3.
- Fabrication and phase analysis of ILM candidate with CdTe and CdS has begun for Task 4.
- Incorporation of ILM in full CdTe cell by end of FY 2010.